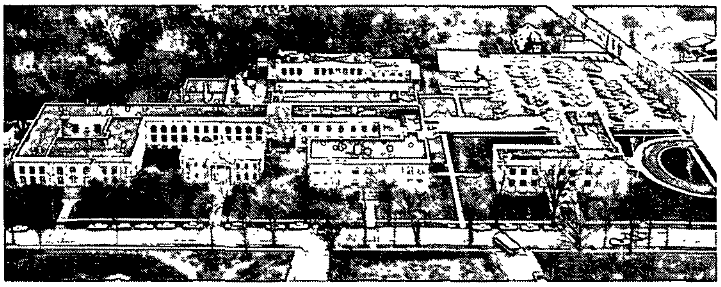
print 14

C Heidemann (2)
K Steppe (2)
H Beauchamp (2)
B Buchinger (2)
J Kennedy (3)
R Pitre (1)
F Rummel (1)
A Oldofer (1)
copies. 14



THE INSTITUTE OF PAPER CHEMISTRY, APPLETON, WISCONSIN

IPC TECHNICAL PAPER SERIES
NUMBER 136

REFINING OF HARDWOODS AND SOFTWOODS

DOUGLAS WAHREN

DECEMBER, 1983

REFINING OF HARDWOODS AND SOFTWOODS

by

Douglas Wahren
The Institute of Paper Chemistry

Summary of presentation to

API Specialty Packaging & Industrial Division
October 13-15, 1983

The main purpose of refining is to develop the papermaking potential of the furnish. This may mean different things in different contexts. If a paper mill has at its disposal only one kind of long fibered softwood pulp, then refining may on occasion serve to improve the formation and smoothness of the sheet by cutting the fibers, thus making them less prone to flocculation. In today's economy, however, this is rarely the case. It is generally advantageous to procure a less expensive, short fibered hardwood pulp and use only the minimum amount of the more expensive softwood to provide the necessary strength properties. Therefore, I consider development of strength the main objective of refining. Even strength properties have different meanings in different contexts; for instance, burst, fold, tensile, tear, pick resistance, etc. For this particular presentation, I have elected to use tensile and tear, but other combinations might be equally useful. It is important, however, to consider at least two properties which normally develop in different directions as refining progresses. Tensile and tear is such a pair. Burst and light scattering coefficient is another.

Refining is a very crude process for imparting changes to the fibers in a way we do not fully understand. As a matter of fact, we do not even understand what sort of changes we want to impart to the fibers. Refining generally occurs

Tomd on the edges and surfaces of refiner bars. Because of the statistical nature of the process, fibers will accidentally break or be damaged in other ways.

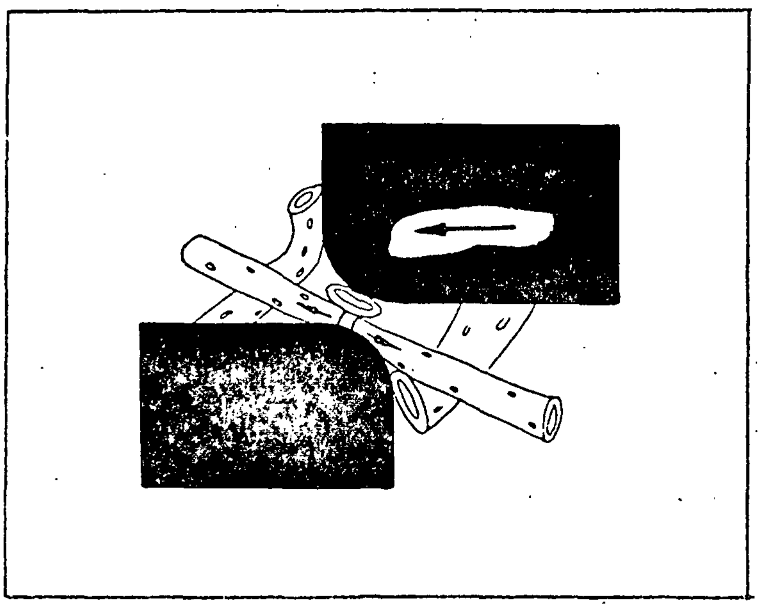


Figure 1. Stresses in refining may break fibers.

This occurs in practice as well as in the lab.

Figure 2. A softwood fiber partially broken in refining.

Another effect of refining is the production of fibrillar material. The micrograph shows an undamaged fiber superimposed on free fibrils produced by refining. This kind of very fine material is termed crill. Crill may have an effect in strength development, but excessive amount of crill, say 5-10%, lowers the freeness and the air permeability of the sheet very dramatically.

Figure 3. An undamaged softwood kraft fiber against a background of "Crill" from the same pulp.

Another effect of refining is external fibrillation, which consists of fibrils and bundles of fibrils dislodged from the fiber wall but still attached to the fiber.

The main desirable effect of refining, illustrated in Fig. 4, is swelling. This micrograph shows very extreme swelling, such as would rarely be seen in practice, but illustrates the point. Swelling seems to be a necessity in the development of strong and stiff paper and board products for reasons that have been explained by Giertz (1).

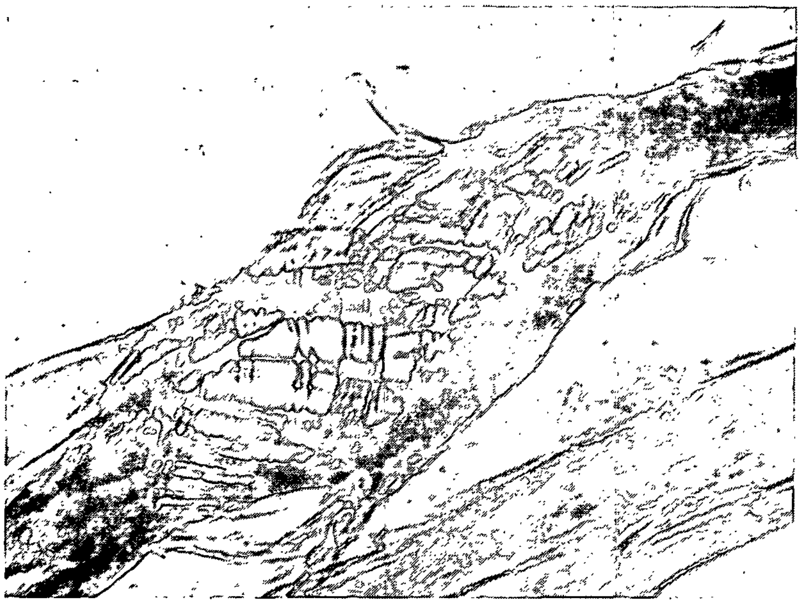


Figure 4. Fibrillation by ultrasonic treatment, according to Algar and Giertz - soft sulphite pulp.

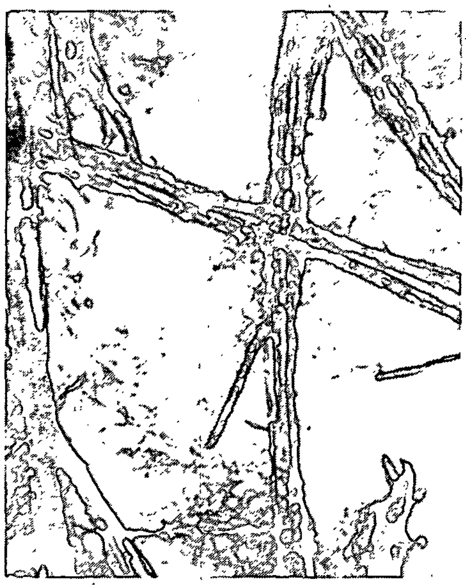


Figure 5. Normal wood fibres from Pinus radiata prepared by the sulphate process and beaten in the Lampen mill for 72 min (x120) - note swelling and the development of external fibrillation (2).

When swollen fibers are formed and consolidated into a paper sheet, they are pulled into very intimate contact by the action of surface tension forces (Campbell forces). As the paper dries, swollen fibers shrink 20-40% in width.

This actually causes axial compression of contacting fibers. When the paper was formed and pressed, some fiber segments were not straight nor under tension. The axial compression effect puts such segments into a state of tensile stress. The resulting paper structure has large built-in stresses, i.e., a design analogous to prestressed concrete. This causes the paper to become stiff, strong, and tough. The stiffness is derived from the activation of virtually all the fiber segments, the toughness from the potential of the axially compressed fibers to stretch. Hence, swelling is a highly desirable result of refining, distinguishing paper from other products such as nonwovens. The bonds in non-woven materials can be made very strong, but the absence of shrinkage during consolidation prevents the structure from becoming stiff.

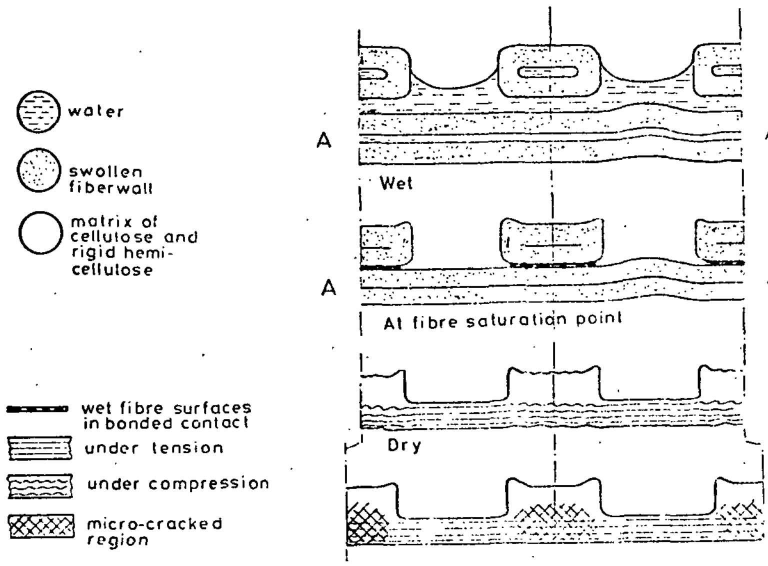


Figure 6. Surface tension forces make fibers shrink laterally during drying. This induces tension throughout the paper structure (3).

In summary, then, I am of the opinion that refining should produce swelling because swelling induces the potential for shrinkage, and shrinkage is necessary to develop the full strength potential of the pulp. Swelling costs money, however. Dr. Atalla and I (4) have calculated that swelling of the fiber requires an effective energy input of about 1 kw-hr/t of pulp per percent of moisture absorbed into the structure. Note that this swelling occurs at the molecular level, whereas we have to cause this swelling to occur by the very crude means of refiner bars that are millions of times larger than the structure we want to treat. Nevertheless, recent results of research at The Institute of Paper Chemistry (5) indicate that of the total swelling measured in well refined pulp, 10-20% of the water, i.e., 15-30% times the mass of the fiber, is absorbed at the molecular level. Hence, it appears that 15-30 kw-hr/t (or 1-2 hpd/t) is effectively consumed at the desired molecular level. This finding seems to point out that the efficiency of the industrial refining process may not be as ridiculously low as has been previously assumed, but may be in the range of 20-50%.

How much abuse?

Having concluded, then, that fibers need to be "massaged" in order to swell, we turn our attention to "how much." How much "abuse" is necessary to cause the desirable changes at the fibrillar and molecular levels, and how much is too much? Preliminary experimentation (6) at IPC indicates that softwoods require stresses of the order of 500 psi to be affected at all, but also that if the stresses exceed about 1500 psi, the risk of fiber fracture is high. For hardwoods, the corresponding range may be 200-600 psi. Effective refining, then, must apply stresses to the fibers within a fairly narrowly defined range. Too low and nothing happens, too high and the fiber breaks. How can this possibly be done?

Good refiners have some degree of control of the stresses. All refiners have a loading mechanism intended for the purpose. The diagram (Fig. 7) has been replotted from data of Danforth (7). It shows tear factor development (or rather the fall off of the tear factor) with refining. The tear factor is plotted against the sheet density, however, because sheet density is intimately related to the internal structure of the sheet. Three runs were made with the same pulp and same refiner, but at three different axial loads on the refiner. Obviously the axial load made no difference to the tear/density relationship.

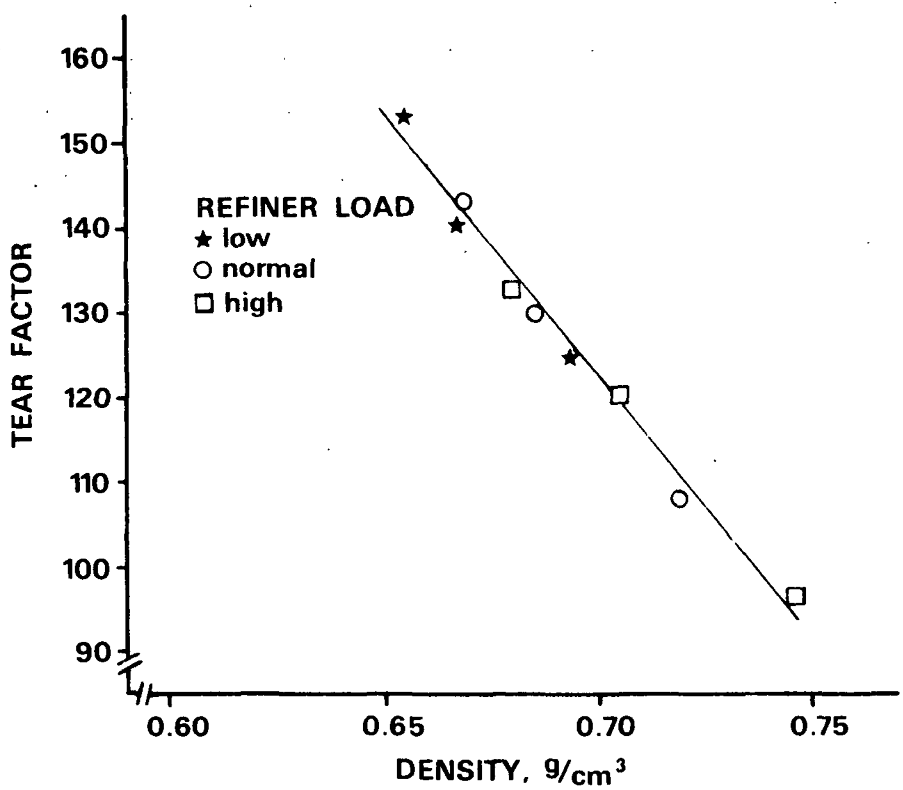


Figure 7. Tear strength vs. density.

Plotting the breaking length against density yields a very different picture.

Breaking length increases linearly with the density at low and normal refiner loads. At the very high load, however, the rate of development of tensile strength levels out, and eventually breaking length drops as refining proceeds. This is a very clear indication of fiber damage caused by excessive stresses on the fibers in the refiner. In mild refining, in the lab or in the mill, the breaking length will increase linearly with density up to the level where further development is limited by the intrinsic strength of the fibers. Most mill refiners will not develop the full strength potential of the pulp but will instead produce pulp with data similar to what is shown here in the case of high refiner load. It is my opinion that the two main factors responsible for this deficiency are refiner overloads and lack of precision in the refiner while operating. Remember that we are speaking here about clearances between refiner surfaces of the order of 3-7 thousandths of an inch, so that a deviation of one mil is a large one. Remember also that the refiner tackle has to be changed many times. The refiner is operating under pressure and at a temperature which is often much higher than that at which the tackle was mounted.

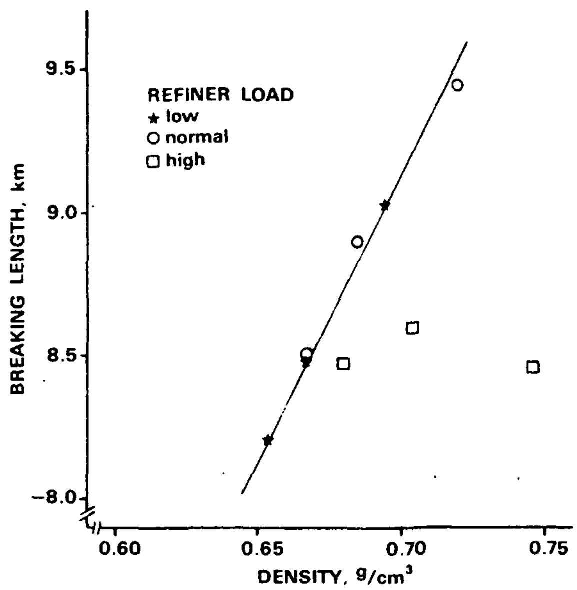


Figure 8. Breaking length vs. density, with axial refiner load as a parameter. The pulp is recycled kraft paper.

Control of the level of abuse

The level of abuse of the fiber in the refiner can be controlled not only by the axial load on the refiner but also by plate design. For any refiner plate it is possible to count and measure the number and length of refiner bars and to calculate the number of "inch contacts per minute", or IC/M for short. This number is calculated in principle as the product of the length and number of bars on the two surfaces times the speed of revolutions. The conventional intensity factor is then designated as

$$\text{Intensity factor} = \frac{\text{net hp}}{\text{IC/M}} \tag{1}$$

where net hp = net horsepower

IC/M = inch contacts per minute.

Note that the net horsepower used here is the difference between the total horsepower applied and the horsepower lost in fluid friction. For high speed refiners, the losses may be very significant; 20-40% is not uncommon, and higher levels of fluid losses can be found. Internationally the intensity factor is expressed as joule/meter, J/m or Ws/m; 1 hp/IC/M = 1.8 MJ/m (mega joule/meter).

These intensity factors are related to, but not an accurate expression of, the stresses on the fibers. As a matter of fact, no such measure exists at the present time, but I hope we will be able to provide one in the future.

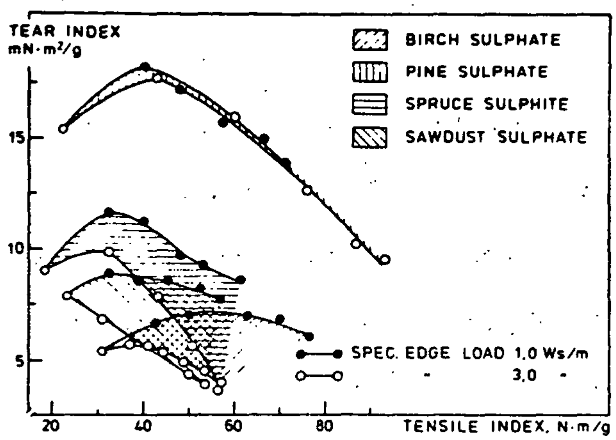


Figure 9. Tear vs. tensile for birch sulphate and some softwood pulps.

J. E. Levlin (8) has demonstrated very clearly the importance of controlling refining intensity, particularly when refining hardwoods for strength. The diagram shows tear as a function of tensile for four different pulps refined at two different levels of intensity. It is obvious that the strong pine sulfate (kraft) fibers will develop equally well at high and low refining intensities, but that more susceptible fibers, such as birch or a spruce sulfite pulp, or a sawdust pulp, all need to be refined at low intensity in order that their potential be developed. Look, for instance, at the birch pulp data. Mild refining (1 Ws/m) developed this pulp to tensile index of 80, i.e., breaking length of 8 km, and the data shows that further development would be possible. Increasing the refining intensity by a factor of three, i.e., to a normal and not very high conventional intensity commonly used for softwoods, causes a lot of damage to the resulting paper properties, probably by damaging the fibers in the refiner.

Similar but even more dramatic results were demonstrated when further increasing the refining severity from 1 to 4 Ws/m. At that level, even the pine kraft experienced some fiber damage and loss of paper properties. Different pulps from different species differ not only in their ultimate papermaking potential but also in their susceptibility to damage by too intense refining.

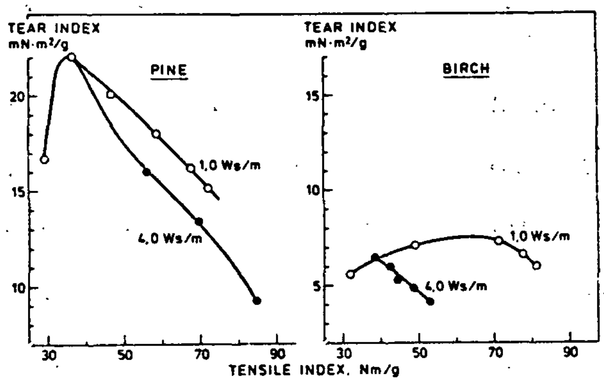


Figure 10. Tear vs. tensile for pine and birch kraft pulps.

Figure 11 demonstrates these points. It appears possible from Levlin's data to develop the Finnish birch to much higher strength levels than appears possible to do with eucalyptus or beech. Note, however, that if the birch pulp were to be refined at a higher intensity level, its properties might drop off and not even equal those of the other species.

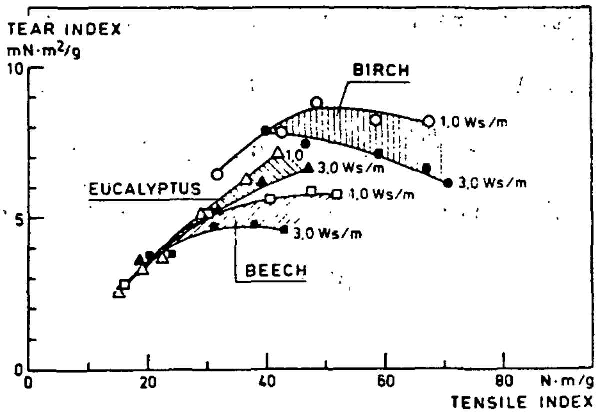


Figure 11. The relationship of tear vs. tensile for different hardwood kraft pulps.

Further experimentation shows that if the refining intensity is further reduced below 1 Ws/m, only small further gains can be made. Laboratory refiners, such as the Valley Beater or the PFI mill, generally operate at very low refining intensities; hence the strength properties developed by such refiners are generally representative of the strength potential of the pulp and generally fall on or just about the properties that can be developed by means of the best industrial equipment. Such data are shown in Fig. 12 which exemplifies the strength potential of some typical chemical pulps.

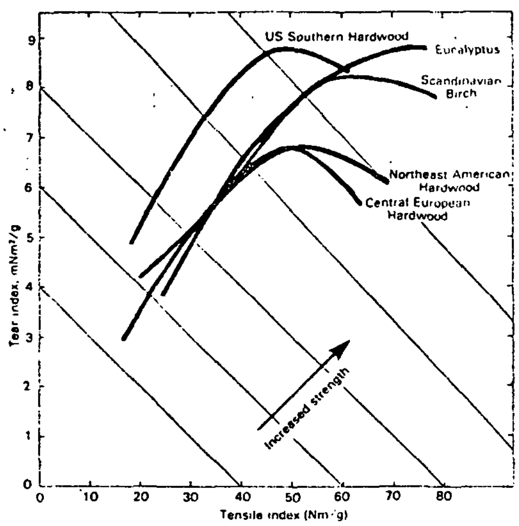


Figure 12. The relationship of tear and tensile strengths of various hardwood pulps (9).

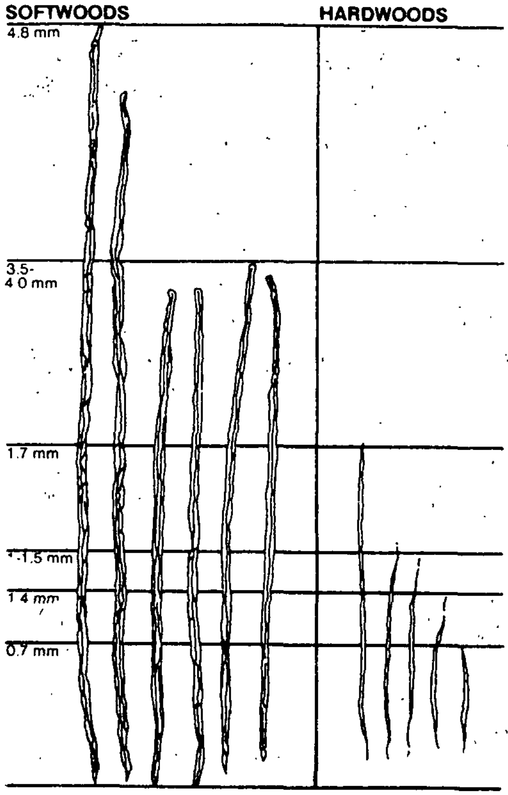


Figure 13. Lengths of fibers from different species of softwood and hardwood.

Hardwoods and Softwoods

Hardwood fibers are shorter than softwood fibers. For papermaking purposes, however, more important is the fact that many hardwood fibers are also very slender. It is the length to effective width ratio of the fibers which determines their characteristics in papermaking and in building the structure of the sheet. The fact that hardwood fibers are so small is advantageous from the point of view of producing a uniform sheet. In softwood pulps, there are generally between one and three million fibers per gram of pulp, whereas with hardwoods the range may be three to twenty million fibers per gram. In thin sheets particularly, the distribution of basis weight from point to point becomes much more uniform the higher the number of fibers per gram. So, let us take a

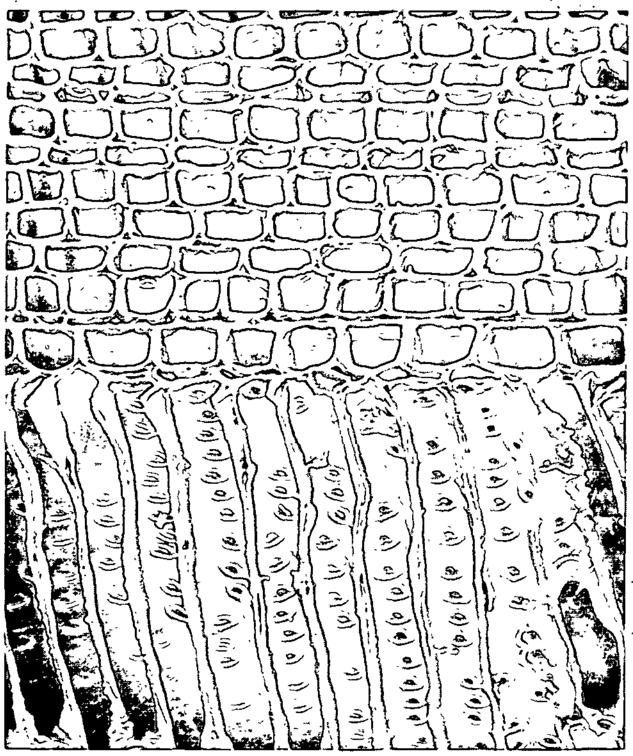


Figure 14. This is a cross section of a piece of jack pine.

look at "typical fibers." You can see that the fibers are arranged in a very regular pattern, that the walls of these fibers are very thin, and that the lumen, or central portion of the fiber, is very large and wide open. These fibers are very straight and very long, and they will collapse if subjected to high compressive stress as they would be, for instance, in refining and wet pressing. This is what papermakers call fibers and botanists call tracheids.

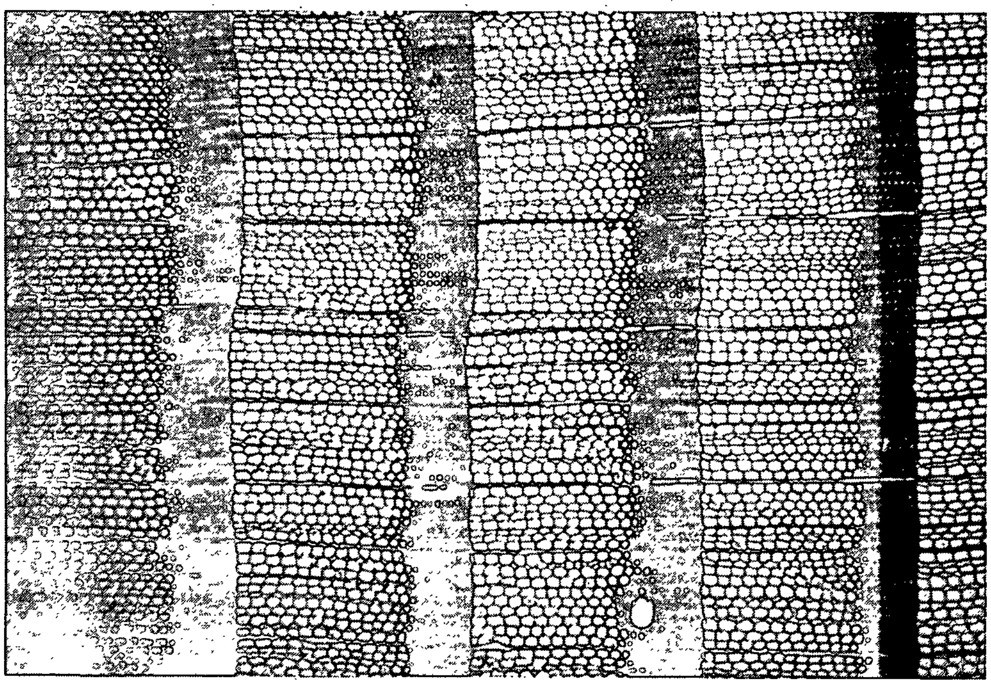


Figure 15. Cross section of softwood (larch).

The tracheids come in two different varieties in most softwoods: the very thin walled ones, which grew very rapidly in early spring, and the much narrower and more thick walled type, which grew slower during summer. As you can imagine, there is a vast difference in properties between springwood and summerwood. This particular piece of wood is larch.

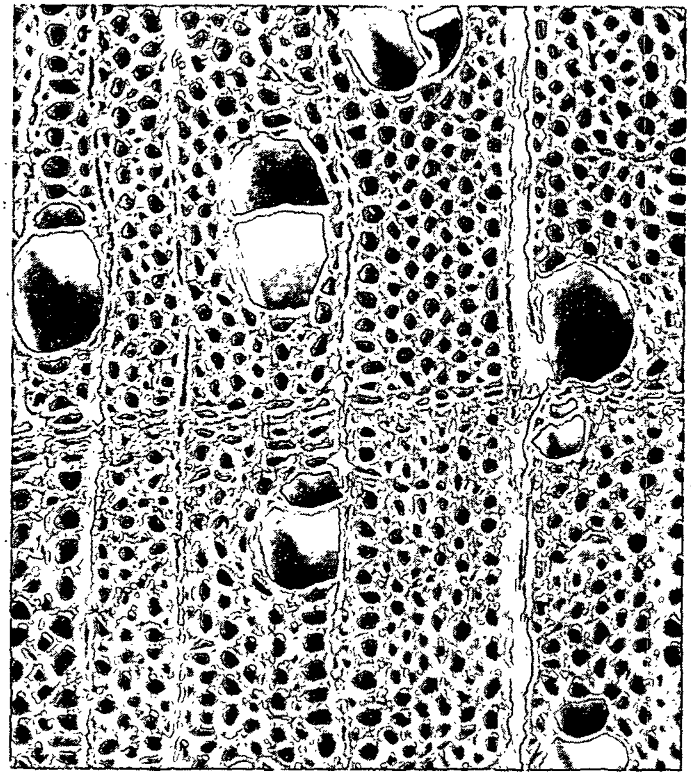


Figure 16. Cross section of white birch.

This micrograph shows a cross section of a typical hardwood with good paper-making characteristics. It is white birch. The vast majority of the cells are tracheids, but you can also see some large openings in the structure representing what is termed vessel elements. The tracheids are fairly uniform with respect to fiber wall thickness. The ratio of wall thickness to lumen diameter is quite high. This implies that the birch fibers are quite stiff and have high compressive strength. Since they are small, they will make a very uniform sheet.

Figure 17. Bleached aspen kraft pulp.

When aspen fibers are pulped and slurried, this is what they look like. The tracheids are rather slender and have all the characteristics of good paper-making "fibers." The vessel elements, however, are rather short and broad and very thin walled. When this pulp is refined the vessel elements will break up, producing debris which lowers freeness and air permeability somewhat without contributing much to strength.

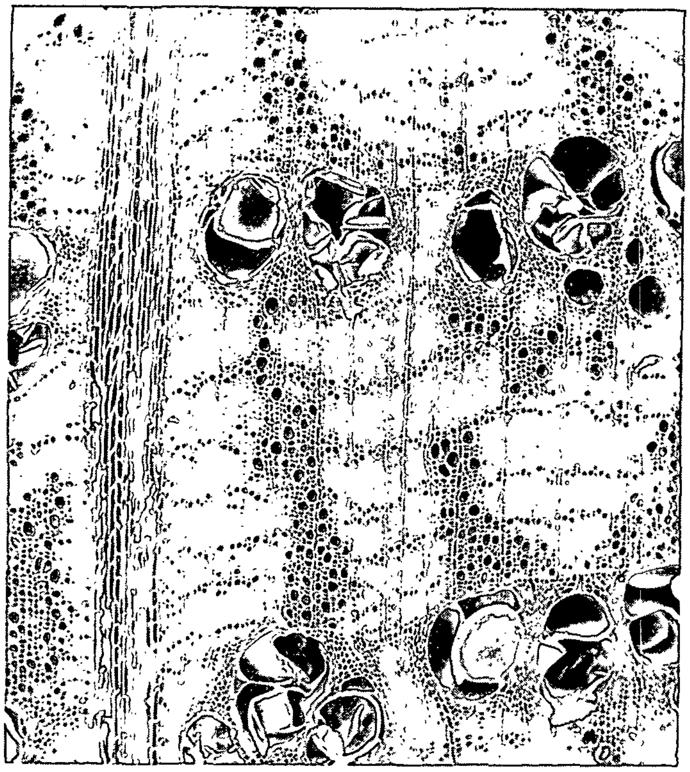


Figure 18. Cross section of white oak.

This is a cross section of white oak. Its cross section is obviously different. Its fibers are very small and very thick walled, and most of them have hardly any lumen. Oaks generally have very high density. You can also see that the oak contains vessel elements.

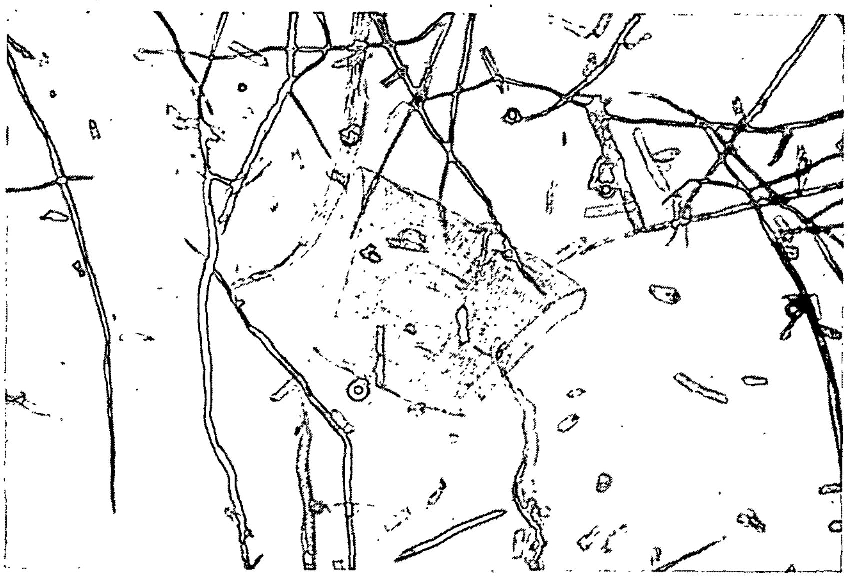


Figure 19. White oak pulp.

When oak is pulped and put into suspension, a significant proportion of the mix consists of tracheids, and a smaller proportion of vessel elements, but there is also a third component, the ray cells (and/or "parenchyma" cells). These small cells have almost the same width as the tracheids, but are very short, so the ratio of length to width is small. In the paper structure, therefore, they will have very few points of bonding. When the paper is stretched there will then be a high risk that the ray cells will debond from the paper causing linting, dusting, and other problems associated with low surface strength.

To summarize: Softwood pulps contain thin-walled springwood and thick-walled summerwood tracheids and not much else, whereas hardwood pulps come in several different varieties. The best hardwood pulps contain a large number of slender thick-walled tracheids and a few thin-walled vessels. Per unit of mass, hardwood fibers are generally stiffer and less collapsible. Because of their smaller size, there is a larger number of them, which tends to have a beneficial influence on formation.

Developing the Potential in Practice

If you are considering the use of an unknown source of fiber, the first thing to do is to assess the papermaking potential of the pulp. This can be done in the laboratory by refining the pulp at different levels of intensity and noting at what levels of intensity pulp properties of interest to you start to deteriorate.

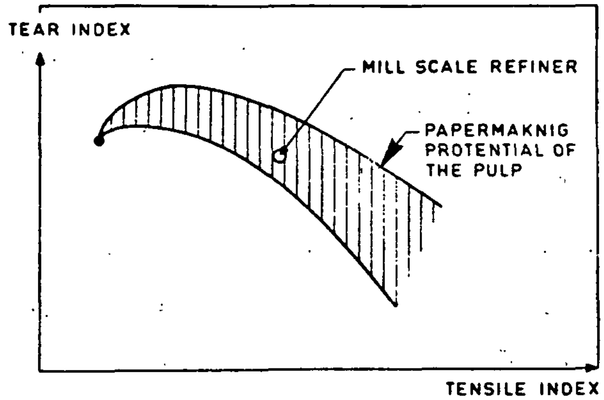


Figure 20. The papermaking potential of a pulp is determined in the laboratory. Actual performance in the mill is determined by the inherent and operating characteristics of refiners in the mill.

It is also necessary to make a proper assessment of the range of refining intensity which might be practically applied in the particular mill.

A balancing act is required. If the refining intensity is kept low, then the rate of production may have to be lower, or you will have to install more refiners. If the intensity of refining is too high, properties will suffer. In general, there is also an energy penalty to be paid when the intensity of refining is kept low.

The rate of production through a refiner is often governed by the pumping characteristics of the refiner. In general, refiners, when regarded as pumps, are expensive, inefficient or downright lousy. Improving the pumping characteristics of refiners is easily achieved by the use "pumping grooves" as part of the plate patterns. This method cannot be expected to improve refining efficiency, however. As the plates wear down, so do the pumping grooves; hence the rate of flow through the refiner and the outlet pressure will vary. It also happens in practice that refiner plates are discarded before their time because of poor pumping characteristics. Refiner plates should be designed for refining. Centrifugal pumps are efficient, cost effective, and easily controlled tools for maintaining flow, and therefore production, at desired levels.

Refining in Different Refiners

The following example is taken from a study aimed at clarifying the functional differences of several refiner constructions. The investigation included a Valley beater and two industrial refiners, denoted as K1 and K2. The refining tests were carried out at a consistency of 2% in the laboratory beater and 3.7% in the industrial refiners. The flow through the refiners, load on the refiner plates, etc., were adjusted according to manufacturers' recommendations. Sheets were produced using SCAN standard methods. The results obtained are presented in Fig. 21-25.

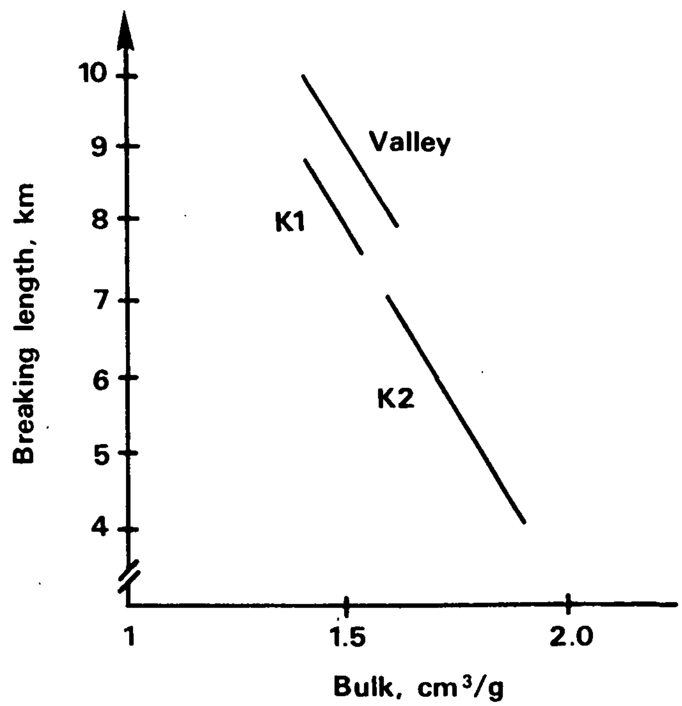


Figure 21. Breaking length as a function of bulk for handsheets formed from the same pulp refined in three different refiners.

Breaking length as a function of bulk is shown in Figure 21. For the two industrial refiners the breaking length is an approximately unique function of bulk, whereas the laboratory beater gives a somewhat higher breaking length at any given bulk. All three refiners, however, produce sheets with different bulks and therefore different breaking lengths. There was some overlap of the ranges of properties produced by means of K1 and K2. The overlapping parts have been omitted for clarity.

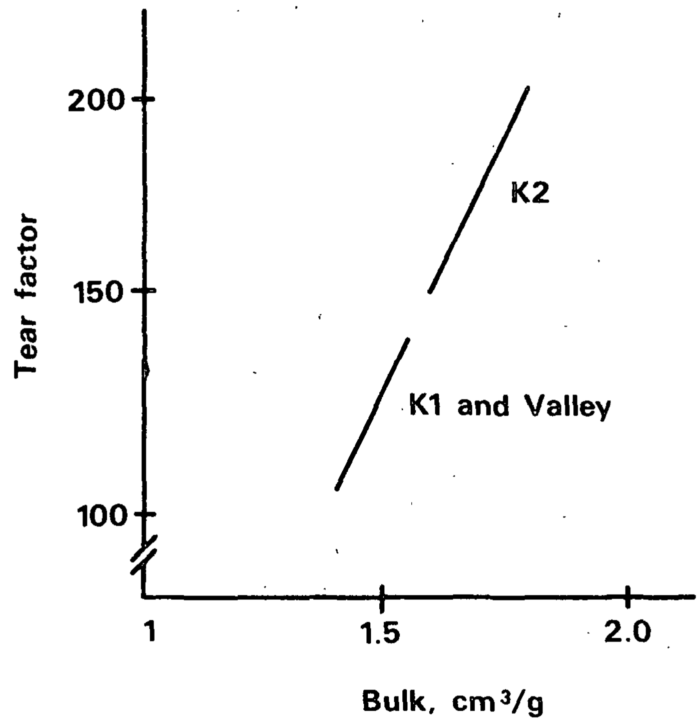


Figure 22. Tear factor as a function of bulk.

Tear factor is plotted as a function of bulk in Fig. 22. The tear factor is a linear function of bulk. The only difference between the way in which the refiners operate lies in the fact that the sheets, because of the different bulks imparted, have different levels of tear.

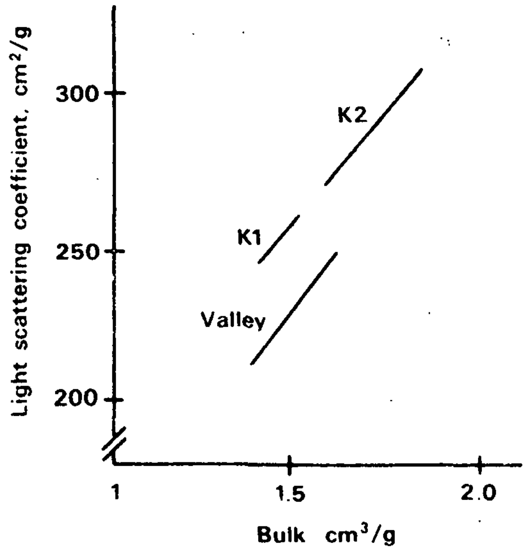


Figure 23. Scattering coefficient as a function of bulk.

Figure 23 presents the light scattering coefficient as a function of bulk. The scattering coefficient increases with increasing bulk for all samples. The laboratory refiner, however, produces a sheet with lower scattering coefficient than the industrial refiners at equal bulk values.

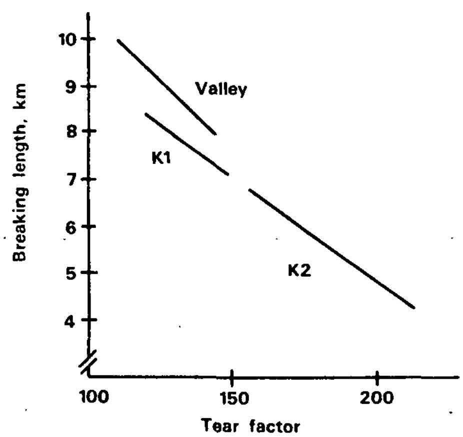


Figure 24. Breaking length as a function of tear factor.

Finally, the relation between the light scattering coefficient and the breaking length is illustrated in Fig. 25. The properties of all of the different stocks lie on a common regression line. Values for energy consumption in kw-hr/ton (mechanical losses excluded) are indicated in this diagram, together with the drainage resistance in °SR (high value equals a low freeness).

From these five figures, several conclusions can be drawn regarding the function of the refiners:

1. At equal tear factor and bulk the Valley beater gives a higher breaking length at the expense of the light scattering coefficient.

2. The tear factor obtained from any one of the refiners depends only on the bulk obtained.

3. In the Valley beater, a given combination of pulp properties is achieved at a significantly lower drainage resistance (°SR) than in the industrial units. (The investigation also included drainage measurements using a rapid dewatering method, where high pressure drops were applied. The results were quite similar to those reported here for °SR).

4. The use of refiner K2 requires considerably more energy than refiner K1 to reach a given combination of properties. The specific energy requirement in laboratory beaters is much higher than in either of the industrial refiners. Due to the enormous difference in machine size, however, an absolute comparison of these values is not possible.

In a choice between refiners K1 and K2, the former is clearly preferable, due to both lower energy consumption and lower drainage resistance, at a given combination of pulp properties.

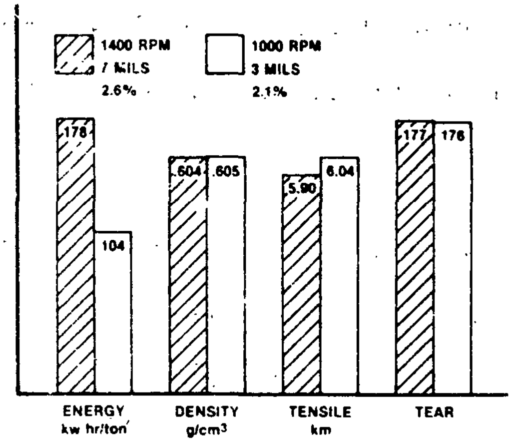


Figure 27. The energy reduction and sheet properties obtained by altering speed, clearance, and consistency.

Figure 27 illustrates the kinds of energy savings that can be achieved on a small industrial scale (12" disk refiner) when refining softwoods. The rotational speed was varied over quite a wide range, maintaining the rate of production (tons per day) through the refiner by means of a separate pump. For the particular kind of fiber, 1000 rpm was the lowest speed, i.e., the one giving the highest refining intensity, that could be tolerated by the fiber. Operating at 1000 rpm compared with the standard 1400 rpm facilitated energy savings of up to 40% while maintaining sheet properties. It is a matter of fact that, in most areas of the United States, energy is so expensive that even a 25% reduction of the energy consumption per ton of pulp would pay for a new refiner, and certainly for a gear box, in less than a year.

Control of Refining

It is not necessary to elaborate further on the necessity for control of refining intensity. This implies control of plate patterns, rotational speed, and axial thrust as means for controlling horsepower.

Obviously it is necessary to control the rate of flow through the refiner. Pumps are suitable means for the induction of flow. Refiner plates should be designed for refining.

It is also necessary to control the amount of refining. The amount of refining is expressed as horsepower-days (or kilowatt-hours) per ton (hpd/T or kw-hr/t). The specific energy applied to the pulp is simply computed as the total hp applied minus the fluid losses when the refiner is running wide open, divided by the rate of production through the refiner.

The simplest control scheme for the refiner is one which will provide only the basic startup and protection systems for the equipment. At best the refiner load is maintained at constant hp. If the rate of flow through the refiner changes, the set point for the load will have to be changed manually. Will this be done?

Many refiner control systems in use today rely in one way or another on the control of couch vacuum. Assuming that the vacuum is induced by a water ring type of pump, such as a Nash pump, the level of vacuum at the couch is a direct function of the air permeability of the sheet on the couch. It will vary the basis weight and speed. If basis weight and speed are constant, then the system will control sheet properties to constant porosity. In a mill having a steady supply of pulp with constant properties, control of refiners via the couch vacuum may be quite sufficient to maintain constant properties of the sheet for modest variations in paper machine speed and other factors.

More advanced systems are on the market, or in the making, but the one control system which makes sense today as a minimum level for industrial application controls the amount of refining. The amount of refining, then, is expressed as hpd/T. Such a system requires measurement of drive power, rate of flow, and consistency. The controller continuously calculates the ratio of the amount of refining to the mass flow of pulp and changes the axial load on the refiner to maintain the set point. The system ensures constant treatment of the fibers even if the rate of production varies over a wide range. Control systems like this generally are built around a microcomputer chip which should be able to communicate with the control system for the paper machine, thus facilitating the changing of set points in response to varying requirements. The system will also compensate automatically for changes of pressure in the refiner.

Note that refiners operated in the traditional manner without feedback control are likely to give varying performance during the life of each set of refiner plates. One reason may be that the rate of flow through the refiner varies. Another reason is that the pressure inside the refiner varies in time. If the operator uses the axial thrust or position as a measure of the refiner setting, then a change in internal pressure will offset the calibration.

Summing up, the basic control parameters are: consistency, flow rate, intensity, and amount of refining. In addition, the pressure and the pH should be maintained within prescribed limits.

Layout of Refining Systems

I do not want to go into the intricacies of engineering refining systems today but just want to make a few points concerning the layout. Refining is in large part an irreversible process. Once a fiber has been refined, it has been refined. Further refining will tend to make it too much refined, causing excessive generation of fines, loss of freeness, and damage to the fibers and ultimately to paper properties. Hence, refining systems should be laid out as a once-through operation without any major recirculation. In the old days, before the advent of practical and reliable process control, pressure in the refiners was controlled by level boxes. Pressure before the basis weight valve on the machine was also maintained by a level box called the stuff box. To keep such systems clean, it is necessary to recirculate a portion of the stock back to where it came from - all too often before a large refiner. Hence, a portion of the stock is refined again and again. Today such systems are neither necessary nor economical. In most cases a pump-through system with flow controllers is less expensive than constructing and erecting level chests and associated stainless pipes.

Another source of recirculation is the broke. Broke, be it wet or dry, needs to be slushed and properly fiberized, with only a small amount of real refining carefully applied to regain the papermaking properties. A separate system for defiberizing and refining the broke and then carefully metering it into the system is recommended. Naturally, the broke should be metered into the system after the last major refiner. In my opinion, the use of "tickler refiners" to perform a major portion of the refining work all too often leads to excessive refining of broke and of the recirculated streams, if any.

Separate versus mixed refining of hardwoods and softwoods can be discussed at length. There is no doubt in my mind that, in a large mill, substantial gains may be made by employing separate systems for the refining of different species. By large, I mean a mill where each stream of pulp is large enough to require a full complement of refiners, chests, and control equipment such that no substantial savings can be made by simply increasing the size of each piece of equipment.

In separate refining, the refining intensity employed for softwoods can be set higher than that employed for hardwoods. Given a number of refiners, it may be possible to turn off one or several refiners or to reduce the speed of refiners, thus employing the highest intensity of refining commensurate with the toughness of the fibers. Doing so may lead to substantial savings of refining energy compared with the energy consumption when reducing the refining intensity to levels compatible with full development of the papermaking potential of the hardwood part of the furnish. Apart from the satisfaction of knowing that each pulp is treated optimally, there is, unfortunately, little reward in separate refining of hardwoods and softwoods in small systems. When refining mixtures, some extra energy must be spent in order to develop both components to their ultimate potential. This energy can be saved when refining separately. There are cases, however, specifically those where the two pulps have radically different properties, where separate refining must be recommended. An extreme example would be straw pulp or bagasse on the one hand and chemical softwood pulp on the other. In such cases, separate refining is a necessity. Otherwise, the choice would be between not refining the softwood component or severely over-refining the other component.

In closing I would like to remind you that the proportion of bleached hardwood pulp to bleached softwood pulp used in the U.S. has climbed from just below 1:4 in the early fifties to 1:1 in 1980 and is still climbing. I believe this reflects the proportion of hardwood used in fine paper grades. The hardwood percentage of the total pulp production in the U.S., which was around 10% in 1945, is approaching 30% today and is still climbing. I believe that economics and logistics dictate that in the long run the ratio of hardwood to softwood usage will approach that which grows in the forests today. It will vary from region to region and it can be impacted by what we do in the way of reforestation, but by and large there is potential for further utilization of hardwoods as a means for obtaining improved economic results.

In thinking about how this potential might be realized, fibers have to be evaluated, pulping processes optimized, and a lot of attention given to refining. We must determine, for each wood species, how much abuse the fibers will withstand. Systems must be adjusted or put in place to implement our intentions. Finally, control systems must be in place to assure continued performance. The potential is there. If we at the Institute can be of any assistance to you at any stage of this process we would be very pleased to help.

References

1. Giertz, H. W. The Effects of Beating on Individual Fibres, Fundamentals of Papermaking Fibres, Transactions of the Symposium held at Cambridge, 1957. p. 389-409.

2. Dadswell, H. E., Wardrop, A. B. and Watson, A. J., The Morphology, Chemistry, and Pulping Characteristics of Reaction Wood. Fundamentals of Papermaking Fibres, Transactions of the Symposium held at Cambridge, 1957. p. 187-219.

3. Giertz, H. W. The Bond Strain Theory of Paper Strength, Saertrykk av Atti del Congresso Europeo, Vienna, Sept. 15-19, 1964. p. G19-G27.

4. Atalla R. and Wahren, D. Energy Requirement in Refining. Tappi 63(6):121-2 (1980).

5. Atalla, R., and Platt, W., private communications, The Institute of Paper Chemistry.

6. Hartman R., Mechanical Treatment of Pulp Fibers for Property Development, Doctoral Dissertation, The Institute of Paper Chemistry, Appleton, Wisconsin, 1983. 127 p.

7. Danforth, D. W., Paper Trade J. 155(37):76(1971).

8. Levlin, J-E., Characterization of the Beating Result, International Symposium on Fundamental Concepts of Refining, The Institute of Paper Chemistry, Appleton, Wisconsin, 1980. p.131-138.

9. PPI Symposium on new pulps for paper, July, 1979. p. 41-46.

Acknowledgment

Thanks are due to Mrs. Barbara Bisby for doing the main job of transforming an audio-visual presentation into written form.